PB82-205899

Application of a Telephotometer to Visibility Measurements in the Eastern United States

(U.S.) Environmental Sciences Research Lab.
Research Triangle Park, NC

1981

U.S. Department of Commerce
National Technical Information Service
NTIS

TECHNICAL REPORT DATA
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1. REPORT NO. EPA-600/J-81-024	2. Journal Article
3. PB82-205899	
4. TITLE AND SUBTITLE: APPLICATION OF A TELEPHOTOMETER TO VISIBILITY MEASUREMENTS IN THE EASTERN UNITED STATES	5. REPORT DATE: April 1982
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S): Thomas G. Ellestad and Ronald E. Speer	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS: Same as 12	10. PROGRAM ELEMENT NO. ADTA1D/01-1106 (FY-81)
	11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS: Environmental Sciences Research Laboratory - RTP, NC Office of Research and Development U.S. Environmental Protection Agency Research Triangle Park, North Carolina 27711	13. TYPE OF REPORT AND PERIOD COVERED
	14. SPONSORING AGENCY CODE: EPA/600/09

15. SUPPLEMENTARY NOTES
REFERENCE: Atmospheric Environment, 15(12):2443-2449, 1981.

16. ABSTRACT

Theories of light extinction and contrast reduction by atmospheric aerosol are reviewed. Measurements by a telephotometer of the relatively turbid atmosphere of the eastern U.S. are described. Because of current levels of extinction, it is feasible to apply a dual target technique first described by Ruhle, which corrects for the targets' imperfect blackness and stray light imperfections in the telephotometer optics. Measurements have been made during an intensive visibility study in the Ohio River Basin. These results compare favorably to independent measures of scattering and absorption coefficients. Complications introduced by uneven illumination due to clouds are found to be surprisingly small; only the most obvious cases of poor illumination need be excluded.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Air Pollution *Visibility *Measurement Aerosols	Telephotometer Eastern U.S.A.	13B 07D

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NATIONAL TECHNICAL
INFORMATION SERVICE
U.S. DEPARTMENT OF COMMERCE
SPRINGFIELD, VA 22161

18. DISTRIBUTION STATEMENT: RELEASE TO PUBLIC	19. SECURITY CLASS (This Report): UNCLASSIFIED	21. NO. OF PAGES: 9
	20. SECURITY CLASS (This page): UNCLASSIFIED	22. PRICE

Atmospheric Environment Vol. 15, No. 12, pp. 2443–2449, 1981
Printed in Great Britain.

0004-6981/81/122443-07 $02.00/0
Pergamon Press Ltd.

EPA-600/J-81-024
Journal Article

APPLICATION OF A TELEPHOTOMETER TO VISIBILITY MEASUREMENTS IN THE EASTERN UNITED STATES

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(*First received* 10 *November* 1980 *and in final form* 7 *May* 1981)

Abstract— Theories of light extinction and contrast reduction by atmospheric aerosol are reviewed. Errors inherent to telephotometry are analyzed. Significant errors may result from unknown target luminance, stray light within the telephotometer, and uneven illumination due to clouds. Measurements by a telephotometer of the extinction coefficient of the relatively turbid atmosphere of the eastern U.S.A. are described. Because of current levels of extinction, it is feasible to apply a dual target technique developed by Rühle, which corrects for the targets' imperfect blackness and stray light imperfections in the telephotometer optics. The results compare favorably ($r = 0.97$, slope = 1.08) to independent measures of scattering and absorption coefficients when the most obvious cases of uneven illumination due to clouds are excluded. The agreement of these two independent measurement methods for extinction coefficient lends credence to them both. However, the difficulty of automating cloud detection for the telephotometer remains a formidable practical problem.

INTRODUCTION

The telephotometer has been used for many years to study optical properties of the atmosphere. The instrument is a telescope having a light detector at its image plane. The detector measures a small and well-defined area of the image, and thus allows the luminance (brightness) of an object to be measured. The telephotometer came into wide use after Koschmieder introduced his theory of contrast reduction by the atmosphere (Koschmieder, 1924). Although the basis of his theory (exponential decrease of contrast with increasing range) was verified by telephotometry, others pursued more general theories of contrast reduction (Middleton, 1952). None of this work, however, has significantly improved upon the usefulness of Koschmieder's theory for dealing with horizontal visibility. With the recent interest in visual air quality spawned by the 1977 Clean Air Act Amendments, telephotometry has again become a popular method.

The past 40 years have seen the advent of another method of visual air quality measurement, integrated nephelometry, which provides a direct measurement of the scattering coefficient (Beuttell and Brewer, 1949; Crosby and Koerber, 1963; Charlson *et al.*, 1967). This quantity (plus its absorption counterpart) is one of the exponential variables of Koschmieder's equation. Thus, if Koschmieder's assumptions are met, a comparison of methods can be made. Each method has some obvious strengths and weaknesses. The purpose of this paper is to present an empirical comparison of the methods and to resurrect a measurement scheme devised by Rühle (1930) that solves several shortcomings of conventional telephotometry.

METHODS

Telephotometry is performed by making luminance measurements of a target, L_T, and the horizon sky, L_H. The apparent target contrast can then be defined as

$$C = \frac{L_T}{L_H} - 1. \tag{1}$$

Applying Koschmieder's theory, one obtains

$$\sigma = \frac{-1}{r} \ln\left(\frac{C}{C_0}\right) \tag{2}$$

where σ = extinction coefficient; r = range; C = apparent target contrast (i.e. at the observation site) and C_0 = inherent target contrast (i.e. at the target).

Many observers use natural targets such as trees or mountains, which are never perfectly black. C_0 should be measured, entailing a trip to the target periodically and an increase in the labor involved. Few observers measure C_0 regularly; most estimate it or ignore it completely, which may lead to serious errors in certain cases. Thus other observers have constructed nearly ideal black targets. This approach has a practical limit since the target must subtend a certain minimum angle as seen from the telephotometer and targets more than a few hundred meters away become prohibitively large and expensive.

Several potential errors in conventional telephotometry can be identified:

(1) Imperfect or uncertain target blackness;

(2) Stray light imperfections in the telephotometer optics;

(3) Horizon luminance differing as seen from the target and from the telephotometer and

(4) Clouds causing uneven illumination.

Comment on error (1). A useful equation to estimate the error involved in computing the extinction coef-

ficient from a target whose inherent luminance is unknown can be derived as follows:

$$\sigma = \frac{-1}{r}\ln\left(\frac{C}{C_0}\right) \tag{2}$$

$$\sigma' = \frac{-1}{r}\ln\left[\frac{(L_T/L_H)-1}{(L'_{TO}/L_H)-1}\right] \tag{3}$$

where σ' = erroneous value of extinction coefficient and L'_{TO} = assumed value of inherent target luminance.

Introducing $F' = L'_{TO}/L_H$,

$$\sigma' = \frac{-1}{r}\ln\left\{\frac{1}{(F'-1)}\left(\frac{1}{L_H}\left[L_{TO}e^{-\sigma r} + L_H(1-e^{-\sigma r})\right]-1\right)\right\} \tag{4}$$

where the terms within brackets represent (a) the true inherent target luminance (L_{TO}) attenuated by extinction, and (b) the air light.

After condensation, we obtain

$$\frac{\sigma'}{\sigma} = \frac{-1}{\sigma r}\ln\left[\frac{1-F}{1-F'}e^{-\sigma r}\right] \tag{5}$$

where σ' = erroneous value of extinction coefficient; σ = true extinction coefficient; r = range; F = true inherent target luminance as a fraction of horizon luminance and F' = assumed inherent target luminance as a fraction of horizon luminance.

Equation 5 demonstrates that the error due to unknown target luminance (or contrast) is a function of extinction coefficient and target range, as well as the accuracy of one's guess of inherent target luminance. Table 1 shows an evaluation of (5) for typical values of F and F', at a variety of ranges for a hazy day and a very clean day. An evaluation of the equation in the user's expected situation may prevent serious problems from arising, for if necessary, he can plan to measure inherent target luminance.

Comment on error (2). All optical systems possess some stray light imperfections from reflections at surfaces and scattering off dust particles on lenses or mirrors and in the tube. It can be imperative to correct for such imperfections, particularly when the target appears very dark, for in such a case the stray light can be a significant fraction of the true apparent luminance. The magnitude of the problem can be demonstrated by two situations we encountered. First, from the Ohio data soon to be presented, a typically observed contrast for a nearly ideal black target was −0.82, which reduces via (2) to an extinction coefficient of 1.2 km^{-1}. This value is about five times the reference value (defined later) and was obviously a great overestimate since our horizon at about 3 km was by no means at the threshold of perception. A second situation arose while measuring the same black target at different distances. Instead of finding the apparent luminance to vary almost in proportion to distance, we found it to have a large and varying offset. For example, at ranges of 33.3, 66.7 and 133.3 m, we expected luminances of 4.1, 7.3 and 13.6 units (corrected for the target's imperfect blackness, F = 0.0010), whereas the measured values were 87.5, 105 and 139. Note that the excesses (83, 98 and 125) show an increasing value as target distance increases, resulting from the increasing stray light as target angular diameter decreases.

Table 1. Ratio of erroneous/true extinction coefficient for a hazy and a clean day

σ (km^{-1})	range (km)	σ'/σ
0.4	100	1.00
0.4	10	1.03
0.4	1	1.33
0.4	0.1	4.34
0.02	100	1.07
0.02	10	1.67
0.02	1	7.68
0.02	0.1	67.8

F = 0.3 = true inherent target luminance/horizon luminance.
F' = 0.2 = assumed inherent target luminance/horizon luminance.

Comment on error (3). One possible cause of differing horizon luminance is curvature of the earth, a violation of Koschmieder's assumptions. However, in the turbid eastern U.S.A., the visual range is short enough that earth curvature effect is essentially negligible. A second possible cause is inhomogeneous aerosol, also a violation of Koschmieder's assumptions. However, our rural location minimized the chances of significant inhomogeneity. These two potential problems were further mitigated by our short path length (161m).

Comment on error (4). The presence of even illumination is one of the fundamental assumptions of Koschmieder's theory. Clouds cause errors of unknown magnitude.

Telephotometry has, however, a number of attributes that offset its problems.

(1) It is a true *in-situ* technique, requiring no sample aspiration that might result in large particle losses and size distribution changes by heating or cooling (as may occur with a nephelometer).

(2) Only the instrument's linearity and zero intercept are important, not its absolute calibration. These can be verified by crossing polarizers at various angles.

(3) Because the telephotometer measures relatively high light levels, a solid-state detector may be used. Such a detector's intrinsic small size, low power consumption, low cost, good linearity and stability, and high reliability offer clear advantages over the photomultipliers necessary in nephelometers.

Rühle (1930) devised a method of correcting for errors 1 and 2 discussed above (Middleton, 1952). This

straightforward optical technique employs two targets similar in shape and inherent luminance and of appropriate size so that, when deployed at two different distances, the targets subtend the same angle to the telephotometer. The observer measures the luminance of both targets and the horizon sky.

For Rühle's method,

$$\sigma = \frac{1}{r_{far} - r_{near}} \ln\left(\frac{C_{near}}{C_{far}}\right) \tag{6}$$

where σ = extinction coefficient; C = contrast and r = range.

An explanation of the method's success is clear when one realizes that identical inherent luminances will divide to unity, as will equal stray light intensities which are a function only of the instrument, horizon luminance, and angular diameter of the targets.

EXPERIMENTAL

Since errors of types 1 and 2 are eliminated by Rühle's design and 3 is negligible, only the error due to non-uniform illumination remains. This was dealt with by classifying the observations by illumination conditions. At the time of observation the observer chose one of three classes.

Class 1. No clouds whatsoever, or very few clouds with none near the target horizon and none casting any shadows along the target sight path.

Class 2. All intermediate situations.

Class 3. Clouds near (within 5°) the target horizon, or clouds casting shadows along the target sight path.

The telephotometer employed closely resembles the commercially available unit sold by Meteorology Research Inc. (MRI). It was operated only with its green interference filter (550 nm). Its objective was of 50 mm aperture and 500 mm focal length. The detector viewed an angle of 2.4 min of arc. The unit was checked for linearity before the study by using crossed polarizers, and its linearity proved excellent (within 1 per cent). The detector response was somewhat dependent on the polarization axis. In the field it was necessary to focus on the object being measured, otherwise the measured luminance was artificially low. This effect prevented our telephotometer from being used in the ratio mode, since when focused on the near target (r = 43.5 m), the sky was out of focus and the ratio was therefore artificially increased. Our far target was a tube 20.5 cm in dia. and 1.22 m long. The near and front edges were cut at 45° and a closure plate was brazed to the rear end. Finally, the inside was painted with optical flat black paint and the outside with medium gray. Measurements of target and horizon luminance made with a broadband photographic light meter indicate our target had a target/horizon luminance ratio of 0.0010. The near target was similar, but about four times smaller. The targets were deployed at the proper distances so that they subtended exactly the same angle as seen at the telephotometer (r_{far} = 161 m, r_{near} = 43.5 m). The telephotometer-to-target bearing was 23° clockwise from north and the sight path was elevated about 1.5° above horizontal. The sight path was about 1.5 m above the ground, which was covered by short grass. The targets were positioned at exactly the same elevation above the horizon as seen from the telephotometer. The pipes supporting the targets were masked with cardboard in order to subtend the same angle.

Our integrating nephelometer was a MRI model 1561. It was operated inside a stationary van about 30 m to the side of the target sight path and drew its sample from an elevation of 5.8 m. Although the van was air-conditioned, the nephelometer sample line was well-insulated, preventing large temperature drops and resulting aerosol growth. As a check, a temperature sensor was installed at the inlet to the nephelometer's scattering chamber and this value was compared to that from an aspirated sensor on the roof of the van. Cooling of the aerosol averaged 1.6°C. A second sensor located at the outlet of the nephelometer's scattering chamber demonstrated that heating of the aerosol while traversing the chamber averaged 0.4°C. The heating results from the hot projector lamp light source used in the nephelometer and was minimized by opening the door of the nephelometer and directing a cooling fan on the lamp and its heat sink.

Several errors can be identified in the scattering coefficient measurement, and consequently, in the reference extinction coefficient. The nephelometer's wavelength response is peaked at 525 nm (Ruby and Waggoner, 1981), somewhat shorter than the telephotometer's 550 nm. Assuming a wavelength dependence of $\lambda^{-1.5}$, one expects the nephelometer's reported value of the scattering coefficient to be about 7% higher than it would be at 550 nm. Ruby and Waggoner (1981) also report revised values for the scattering coefficient of Freon-12, used to calibrate our nephelometer. We had used 0.212 km^{-1} as the calibration value, whereas the revised value for the site's altitude is 0.187 km^{-1}. Thus, due to outdated calibration values, our values of scattering coefficient were about 13% high. The error of the nephelometer due to the design defect of angular truncation is estimated by Ensor and Waggoner (1970) to be −4–10% for "typical" atmospheric aerosol. The combined effect of these errors is that our values of scattering coefficient are estimated to be 9–17% high. Since scattering was about 90–95% of extinction, we conclude that our values of reference extinction coefficient are systematically about 9–15% high, compared with an absolute measurement at 550 nm. The data have not been revised, however, since the correlation coefficients would not change. Only the slopes of the linear regressions would change, becoming for Figs 2 and 3, values of about 1.08 and 1.02.

The particle absorption coefficient was monitored over 2 h intervals using the integrating plate method of Lin *et al.* (1973). Absorption was found to be small—usually only 5–10% of extinction.

Measurements were made at a rural site about 70 km southeast of Columbus, Ohio. Site coordinates were latitude 39° 23′ 18″ north and longitude 82° 27′ 36″ west, and the site altitude was 302 m. Our site was atop one of the rolling hills of southeastern Ohio, where local land use was primarily agricultural, although coal strip mines were located within several km north and east of the site.

The sequence of operations for a telephotometer measurement was to check zero, measure luminances of near target, far target, and sky, check zero, estimate illumination class, and measure sun angle by protractor. Simultaneously, readings were being made of the nephelometer output, temperature difference between nephelometer and ambient, and relative humidity. 82 observations were made during daylight hours from 15 to 31 July 1980. Observations were usually about 1-h apart.

Analysis consisted of computing Rühle's extinction coefficient from telephotometer data and a reference extinction coefficient (the sum of coefficients of Rayleigh scatter, particle scatter from the nephelometer, and particle absorption from the method of Lin). Light absorption by nitrogen dioxide was not included in calculating the reference extinction coefficient because the mean NO_2 concentration was only 9.3 μg m^{-3}, corresponding to an absorption coefficient of about 0.001 km^{-1}. Linear regression was then performed between Rühle's σ and the reference σ. Linear correlation coefficients were computed among all variables. Finally, linear correlation coefficients were calculated for subsets of the data classified by illumination class, relative humidity, and several other parameters.

RESULTS AND DISCUSSION

Figure 1 shows the scattergram of Rühle σ vs reference σ for all observations. By eliminating class 3 data, the correlation coefficient increased from 0.84 to 0.97 (Fig. 2). Telephotometer data were in remarkably good agreement with the reference values over a wide range of extinction coefficient when there were no

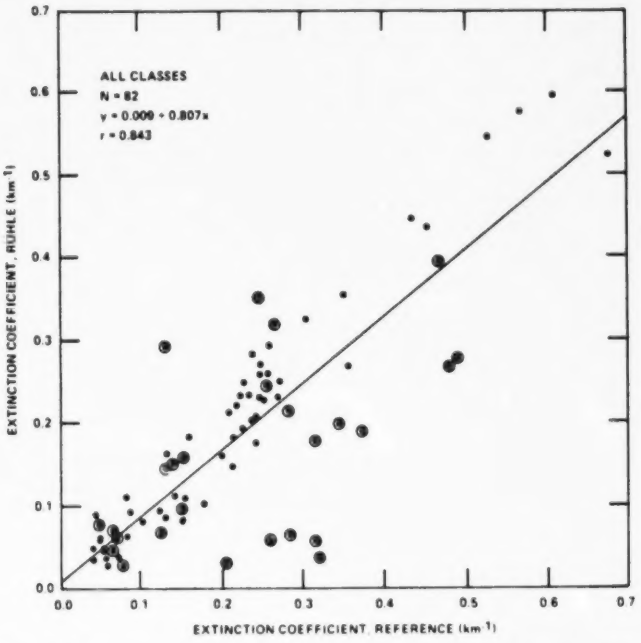

Fig. 1. Scattergram of extinction coefficient from telephotometer vs reference extinction coefficient for all classes (1, 2 and 3). Class 3 encircled.

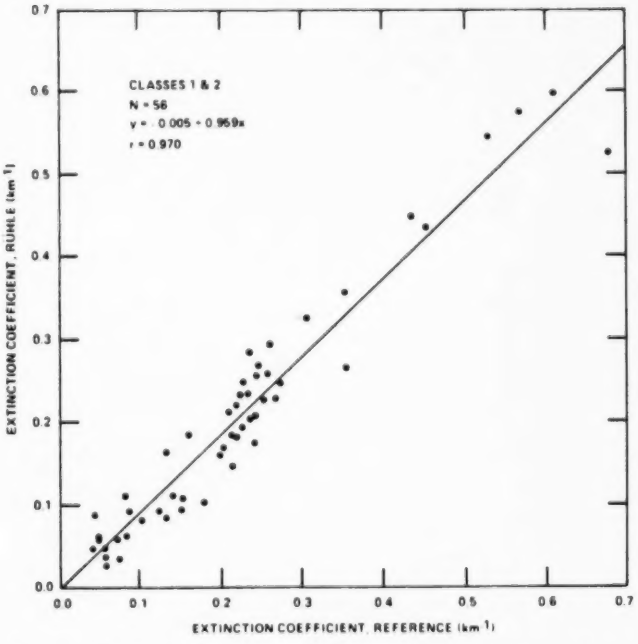

Fig. 2. Scattergram of extinction coefficient from telephotometer vs reference extinction coefficient for classes 1 and 2.

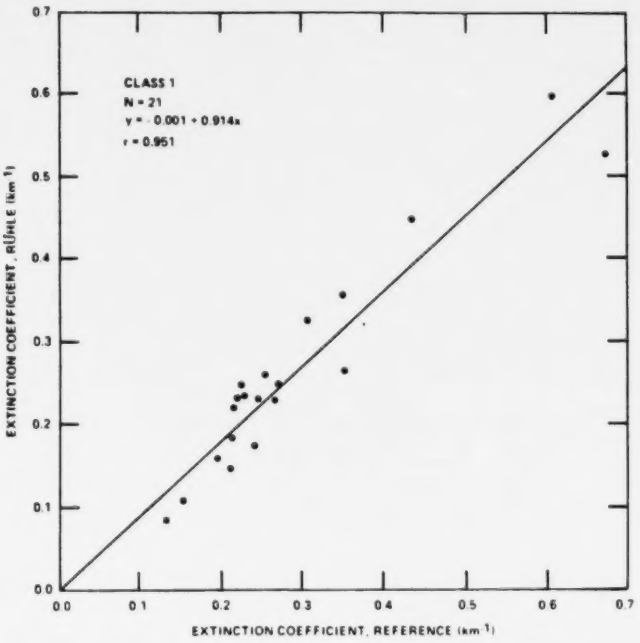

Fig. 3. Scattergram of extinction coefficient from telephotometer vs reference extinction coefficient for class 1.

clouds within 5° of the target horizon or casting shadows on the sight path. Surprisingly, eliminating class 2 data as well resulted in no improvement of the regression (Fig. 3). Since comparing correlation coefficients of non-independent data sets can lead to erroneous conclusions, linear correlation coefficients of individual illumination class data were calculated. Class 1 data had a correlation coefficient of 0.95 (N = 21), class 2 of 0.98 (N = 35), and class 3 of 0.55 (N = 26).

Classification of the data by parameters other than illumination conditions resulted in no significant improvement of the correlation. Classification by ambient relative humidity showed little effect on the correlation for class 1 and 2 data; however, all of the 56 cases had relative humidities below 70%, a range in which humidity effects are not expected to be great. Classification by temperature difference between ambient and nephelometer inlet indicates that aerosol cooling/heating during aspiration into and through the nephelometer accounted for some of the deviations between the two methods. The correlation coefficient between methods improves slightly but steadily as one restricts cases to tighter tolerances of ΔT (see Table 2). The sun angle (i.e. scattering angle) had no discernible effect, although, because of our northerly orientation the sun angle varied only from about 80–111°.

Table 2. Correlation coefficient between methods for class 1 and 2 data at various tolerances of ambient-nephelometer temperature difference

ΔT(°C)	r	N
0.5	0.992	12
1.0	0.988	22
1.5	0.988	27
2.0	0.984	36
2.5	0.983	37
3.0	0.968	46
4.0	0.968	49
5.0	0.968	51
6.0	0.968	53
7.0	0.970	56

While appealing in its simplicity, simple target contrast of a nearly-ideal black target should not be used because its measurement does not correct for stray light problems. The absolute value of contrast will be in error by an amount depending on the telephotometer, target, and target distance in use, thus observations from different systems cannot be easily compared. Figure 4 shows the scattergram of apparent far target contrast vs reference σ for classes 1 and 2. The correlation coefficient is nearly as good as with

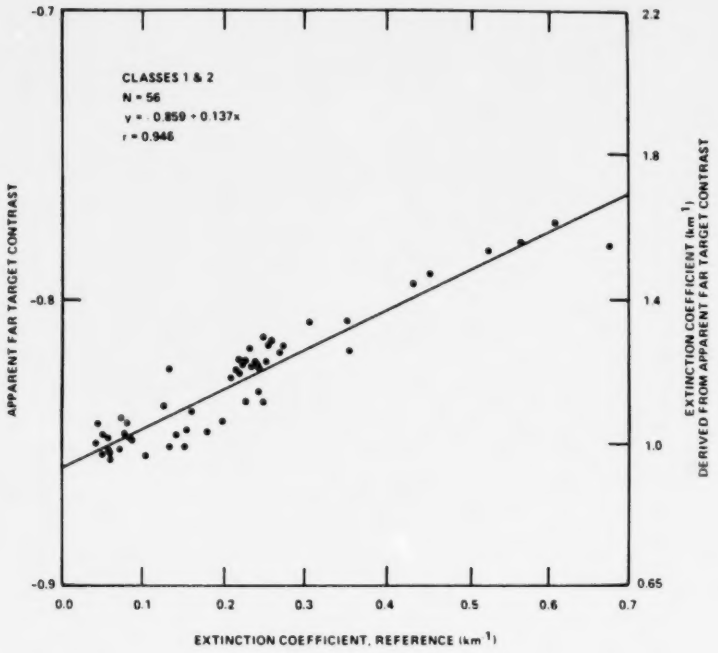

Fig. 4. Scattergram of far target contrast vs reference extinction coefficient for classes 1 and 2.

Rühle's extinction coefficient. Figure 4 also shows on its right axis the extinction coefficient derived from the apparent far target contrast using (2) with $C_0 = -0.999$. There are obvious gross discrepancies between this estimate of extinction coefficient and the reference value for our particular apparatus and configuration. Less stray light within the telephotometer or longer path lengths could significantly reduce the discrepancy.

Though the telephotometer method is a path measurement and the reference extinction measurements were made at a point, little can be inferred about their agreement as point and path measurements because, at our rural site, the aerosol could probably be expected to be homogeneous within 200 m.

A limitation of the analysis has been the relatively small number of observations. Classifying the data too far can result in a dangerously low (< 10) number of observations.

Rühle's method of telephotometry is not a panacea. One must find suitable terrain to deploy the targets. They must be collinear, be properly spaced, permit a clear view of the horizon sky, and be reasonably horizontal, criteria not always easy to achieve. The targets must be maintained at the same inherent luminance, which necessitates frequent checks and periodic cleaning and repainting. In very clean air longer sight paths and larger targets may be required. Finally, Rühle's method makes no attempt to correct for the presence of clouds.

Despite the good agreement of telephotometry and integrating nephelometry reported herein, it is not correct to call them equivalent measurements. The telephotometer is clearly a better instrumental approximation to the eye than is the nephelometer. Like the eye, the telephotometer is influenced (even with Rühle's method) by snow on the ground, looking toward the sun, and clouds. But because of these attributes, the telephotometer is surpassed by the nephelometer as an indicator of fine aerosol mass loading and aerosol optical properties. Both instruments have a place in visibility measurement and research programs.

CONCLUSIONS

(1) Measurements of the light extinction coefficient (or visual range) by telephotometry are subject to several sources of error: unknown target luminance, stray light within the telephotometer, differing horizon luminance as seen from the target and the telephotometer, and uneven illumination due to clouds. Uncertain target luminance may cause substantial error in cases of small extinction coefficient or ranges significantly less than the visual range. Stray light within the telephotometer optics may cause substantial error when using black targets, especially at short ranges.

(2) Rühle's method of telephotometry eliminates the problems of uncertain target luminance and stray light.
(3) Clouds may cause considerable errors of either sign when they appear behind the target or cast shadows on the sight path. Suitable criteria for excluding such cases still allow many non-cloud-free observations to be included.
(4) Measurements of the light extinction coefficient by telephotometer and integrating nephelometer agreed well when Koschmieder's assumptions were met and telephotometer stray light problems were overcome.

Acknowledgement—The authors wish to thank R. C. Nininger, R. A. Carlson, and W. S. Crews of Northrop Services, Inc. for their work in making the Ohio observations.

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